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ABSTRACT.

In a fusion reactor with high energy-gain, the fusion power will be mainly THermo-Nuclear (THN). Measurements of the THN neutron rate are a good performance indicator of a fusion plasma, requiring Neutron Emission Spectroscopy (NES) measurements to distinguish thermal and non-thermal contributions. We report here on recent NES results from JET high-performance plasmas with high fractions (about 65%) of THN emission. The analysis is made with a framework for analyzing NES data, taking into account THN reactions and beam-target reactions. The results are used to extrapolate to the equivalent DT rates, Finally, we discuss the applicability of using NES in the deuterium phase of ITER, both for the extrapolations to ITERs future DT performance as well as for measurements of confined energetic ions.

1. INTRODUCTION

In a fusion plasma, it is readily shown that reactions from accelerated ions can never be a net source of energy since too much energy is lost in the acceleration. Consequently, in next generation fusion reactors with high energy gain ($Q = P_{FUS}/P_{AUX} >> 1$) the fusion reactions need to be predominantly of thermonuclear origin. For t(d,n)^{4}He (DT) reactions, the thermonuclear reaction rate per unit volume scales as $I_{THN} = n_d n_t <\sigma v>_{DT}$, where nd and nt are the deuterium and tritium densities, respectively, and $<\sigma v>$ is the reactivity; for d(d,n)^{3}He (DD) reactions in a deuterium plasma, the reaction rate scales as $I_{THN} = n_d n_t <\sigma v>_{DD}$. Maintaining a high fuel-ion density is thus critical for optimum fusion performance, which in turn requires a clean plasma that is not diluted by impurities. However, extracting the fuel ion density through the effective charge (Z_{EFF}) of the plasma can sometimes be difficult, and since the thermonuclear reaction rate scales as the square of the fuel ion density, small errors can have a large impact. Therefore, predictions of the fusion power can be difficult to make.

On the other hand, measurements of the thermonuclear emission can serve as a good indicator of the plasma performance, and the fuel ion density can be deduced from the intensity of the emission (I_{THN}). Further, in a fusion reactor operating with deuterium plasmas, the equivalent DT fusion power (i.e., assuming half of the fuel is replaced with tritium) can be projected from the thermonuclear DD emission and the ratio of the DD and DT reactivities. However, the thermonuclear emission is normally accompanied with neutron emission from Beam-Thermal (BT) and Beam-Beam (BB) reactions, which makes the total neutron rate difficult to interpret as a performance indicator; the emission must therefore be separated in its components.

In this paper we present Neutron Emission Spectroscopy (NES) measurements of JET deuterium plasmas. A model taking into account THN and BT neutron emission is employed to extract the different components, and the results are used to estimate the fuel ion density, nd, as well as to project the equivalent DT performance of JET.

2. EXPERIMENTAL

Two neutral beam heated JET discharges are studied in this paper, Pulse No's: 69992 and 79698.

Both are high-density plasmas with *n*e peaking around 1.1×10^{20} and with heating powers around 20MW. While the two discharges are similar in that context, the current and magnetic field was different with $B_T = 2.9$T and $I_P = 3$MA for the former and $B_T = 3.6$T and $I_P = 4.5$MA for the latter. This

has great consequences on the plasma performance as shall be seen later. The effective charge (Z_{EFF}) measured by visible bremsstrahlung was around 1.5 and 2.0 for Pulse No's: 69992 and 79698, respectively. Assuming carbon is the dominant impurity in the plasma, this corresponds to hydrogenic densities (i.e., summed hydrogen, deuterium an tritium) at 90% and 80% of the electron density.

The neutron spectroscopy measurements presented in this paper are made with the time-of-flight spectrometer TOFOR [1], which is installed in the JET roof laboratory, and views the plasma radialy from above the tokamak at a distance of 19 meters from the plasma center. TOFOR consists of two detector sets with 5 primary scatterers (S1) and 32 secondary scatterers (S2). The flight path between S1 and S2 is around 1.2 meters and the scattering angle is 30°. This results, to first order, in a flight time $t_{TOF} = 65$ns for neutrons with $E_n = 2.5$MeV.

The measured neutron spectra are analyzed with a Bayesian fit to the t_{TOF} data, where the neutron emission is separated into spectral components and folded with the TOFOR response function; see e.g. [2] for examples of similar analysis. Two components, describing thermonuclear (THN) and Beam Target (BT) reactions and one component describing scattered neutrons, are used here. The THN spectrum is modeled as a Gaussiancentered at 2.47MeV and with a width $\sigma_{THN} = 35\sqrt{T}$ keV. The ion temperature measured by Charge eXchange Recombination Spectroscopy (CXRS) is given as a Bayesian prior to the fit and the BT spectrum is calculated assuming a beam ion slowingdown distribution reacting with a thermal plasma. The spectrum of scattered neutrons is calculated with an MCNPX model of the JET vacuum vessel [3].

3. RESULTS

The measured time of flight spectra for the two discharges are shown in Figure 1 (a) and (b) as points with error bars. For both discharges, the spectra are dominated by a peak between 60 and 70ns, which corresponds to neutron energies between 2 and 3MeV. Towards higher flight times (lower neutron energies), a tail with an intensity of about 10% of the main peak is also seen. This tail is due to energy-degraded neutrons that have scattered either in the spectrometer or in the reactor vessel. The spectra shown are from the periods of peak neutron emission for the two discharges, with total neutron rates $R_{NT} = 6.2\times10^{15}$ s^{-1} for Pulse No: 69992 and 1.6×10^{16} s^{-1} for Pulse No: 79698. This results in coincidence count rates in TOFOR of 18 and 39kHz, respectively.

Together with the measured data in Figure 1, the fitted spectral components are also shown after folding with the spectrometer response function, and in Figure 2 they are shown on a neutron energy scale. Finally in Figure 3 the time evolution of the fitted THN and BT fluxes on TOFOR, Γ_{THN} and Γ_{BT}, are shown. For both discharges, the beam heated period starts with a transient phase that is dominated by BT emission (dashed blue). However, as the temperature and density of the plasmas builds up the THN emission increases. For discharge #69992 the THN flux levels out at 42% of the total neutron emission while for discharge #79698 it reaches a level of about 65%. In absolute terms, the THN emission from the latter discharge is about 3 times higher than for the former. We also see that the difference in total neutron emission for the two discharges is entirely due to the increased thermonuclear neutron rates, i.e., the BT rates are about the same for the two discharges.

Using the thermonuclear neutron emission, the density of the fuel ion population can be estimated from the reactivity of the DD reaction by rewriting the expression for the emissivity (*I*THN) as *n*d = (2*I*THN / <√v>DD)1/2. However, TOFOR does not measure the emissivity (*I*THN) but a line integrated flux (ìTHN). In this paper, *I*THN is approximated from ìTHN measured by TOFOR according to *I*THN = ìTHN/©*V*LOS, where © is the solid angle of the sight line, and *V*LOS is the volume of the core plasma viewed by TOFOR. The solid angle of the sight line is known (about 2"≈10-6 str), and *V*LOS is obtained by scaling ìTHN with the total neutron rate using the method described in [4]. The deduced *n*d for the two discharges are shown in FIG 4 as points with error bars. Also shown are the electron density *n*e (solid blue) and *n*d derived from *Z*EFF measurements (dashed red). For the density derived from *Z*EFF it assumed that the hydrogen isotopes are deuterium only.

Uncertainties of the input parameters are handled as follows. First, for *I*THN there are mainly three contributing factors: the statistical uncertainty from the fit to the TOFOR data, how the uncertainty in the ion temperature is reflected in <√v> and the uncertainty in the estimate of the core volume. While the good statistics of the TOFOR data makes the first contribution low at a few percent, the 2nd and the 3rd are dominating. The uncertainty in *T*i measurements with CXRS is quoted to be 10%; for the temperatures of interest here, around 6 keV, this amounts roughly to a 30% uncertainty in <√v>. The uncertainty in *V*LOS is a bit more difficult to determine, but 20% should be considered a rather conservative estimate. The total uncertainty in *n*d is then around √nd = 1/2 “≈ (0.32 + 0.22)1/2 ≈ 20% and includes both systematical and statistical contributions.

A TRANSP [5] simulation of JET discharge #69992 was studied to evaluate the consistency of the neutron analysis (FIG 5). Using the measured *Z*EFF as input to TRANSP, the neutron rates predicted by TRANSP (dashed black) were about 60% higher than the measured rates (dotted red). However, manually setting the input *Z*EFF to 2.5 (compared to the measured 1.5) results in a good match between measured and predicted neutron rates (solid blue). The core deuterium density corresponding to *Z*EFF = 2.5 is shown in FIG 4 (solid black). Evidently there is a good agreement between the deuterium density derived from the thermonuclear flux measured by TOFOR and that required by TRANSP to match the total neutron rates.

Finally, since the fraction of THN and BT emission is known from the TOFOR data, the total DD neutron rates can be used to extrapolate to the equivalent DT performance, i.e., assuming the same temperature and NBI heating, but replacing half of the deuterium with tritium and scaling with the ratio of the DD and DT reactivities. We find that Pulse No:79698, which has a peak DD neutron rate at $R_{DD} = 1.6\times10^{16}$ s^{-1}, would reach a peak DT rate at 1.9×10^{18} s^{-1}. This corresponds to 5.4MW of fusion power or an energy amplification of $Q = 0.21$. Integrated over the full plasma discharge, the total fusion energy produced would be 24.5 MJ. This can be compared to the present record at 22MJ for a real DT discharge, which was obtained in JET Pulse No: 42982 [6].

4. DISCUSSION

The thermonuclear (THN) neutron emission from two JET discharges was extracted using the TOFOR spectrometer. While the discharges were very similar in terms of heating and plasma density, one discharge had a considerably higher plasma current, $I_P = 4.5$MA compared to $I_P = 3.0$MA. This results in a better plasma confinement and hence higher temperature, which in turn is seen in the THN neutron emission, which increased by a factor of 3. This clearly demonstrates the improved fusion performance from an increase in the plasma current.

However, high energy confinement and plasma temperature is not the entire story of high fusion power. The thermonuclear reaction rate scales as the square of the fuel ion density. If the plasma is contaminated by impurities from the wall, or in the case of a burning plasma also by accumulated helium ash, the fuel ions will be diluted, and the fusion power will decrease. In this paper we use the measured thermonuclear emission to calculate the fuel ion density. The advantage of using the thermonuclear emission, rather than the total neutron rate, is that it only depends on the fuel ion density and temperature. If one of the parameters is known, the other can be deduced. On the other hand, the total neutron rate also includes the BT emission and thus depends on the beam ion distribution as well. This typically needs to be calculated introducing more uncertainties in the estimates.

For both discharges studied here, the fuel ion density was found to be around 60% of the electron density, or 7×10^{19} m^{-3}. Compared to the densities derived from ZEFF measurements, these numbers are some 20-40% lower as shown in FIG 4. For Pulse No: 69992 the difference is significant, but for Pulse No: 79689 it is close to the estimated systematical error. Here we shall not speculate much about what could be the cause of the discrepancy for Pulse No: 69992, but we note that it should partly be due to the hydrogen in the plasma, which is not a fuel ion species and is thus not measured by neutrons.

In the TRANSP simulation of Pulse No: 69992, no consistency checks were made for other parameters such as total plasma energy. This was considered out of the scope of this paper, which is merely intended to demonstrate how the thermonuclear fusion performance of a plasma can be measured already in deuterium operations using a neutron spectrometer. However, a more systematic survey of TOFOR data, TRANSP simulations and Z_{EFF} measurements will be the focus of future word.

Due to the quadratic relation between fusion power and ion density, an uncertainty of 10% in the fuel ion density would amount to an uncertainty of 20% for the fusion power. In a DT plasma at JET, this is equivalent to about a MW, but at ITER such differences could amount to 100MW or more. Clearly, optimizing the fuel ion mix is of outmost importance for successful operation of a fusion reactor. In this paper we have shown how Neutron Emission Spectroscopy (NES) can be used as a powerful tool to study the thermonuclear performance of the plasma already during deuterium operations. At ITER, a spectrometer that can separate the THN emission during the deuterium phase will be a highly valuable tool. Due to the high injection energy of the beams, about 1MeV, the BT reactivity will be very high, and the DD neutron emission will always be dominated by BT reactions, even for high-performance operations. Using the total DD neutron rates to asses the plasma performance will therefore be very difficult. In Figure 6, the estimated THN and BT spectra from ITER deuterium operations are shown.

It can be worth to notice here that the high energy of the NBI heating at ITER will create BT spectra reaching up to about 3.5MeV, which is considerably wider than the thermonuclear emission (FIG 6). This is in contrast to the situation at JET where the BT and THN emission strongly overlaps. This allows for using the part of the DD emission with $E\text{n} > 3.0$ MeV as an effective probe of energetic beam ions. A neutron spectrometer operating during the deuterium phase of ITER could thus be used both to measure the plasma performance as well as to measure fast ions.

CONCLUSIONS

In this paper we have shown how neutron spectroscopy measurements can be used to separate the thermonuclear neutron (THN) emission from the beam-target (BT) emission at JET. The THN emission is a direct indicator of the plasma performance and can be used both to extract the core ion temperature and the core fuel ion density. The densities extracted from TOFOR data agrees with those estimated from TRANSP simulations but are systematically below estimates from Z_{EFF} measurements.

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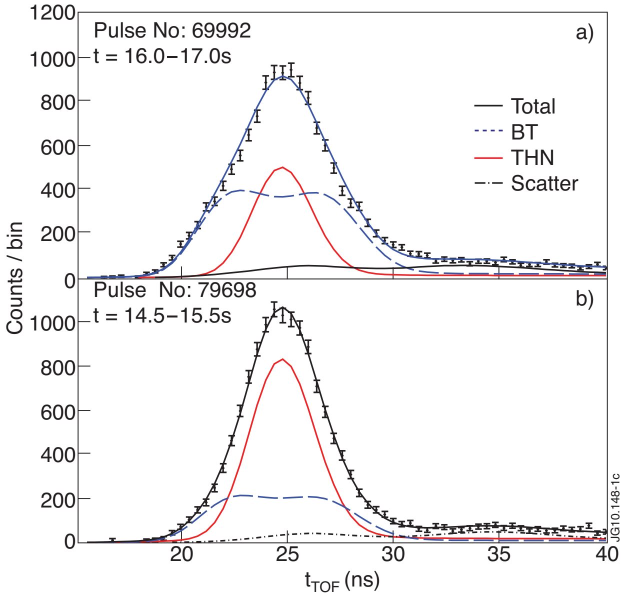

Figure 1: TOFOR data from JET Pulse No's: 69992 (a) and 79698 (b) as well as the fitted components THN (solid red), BT (broken blue) and scatter (dash-dot-dot black).

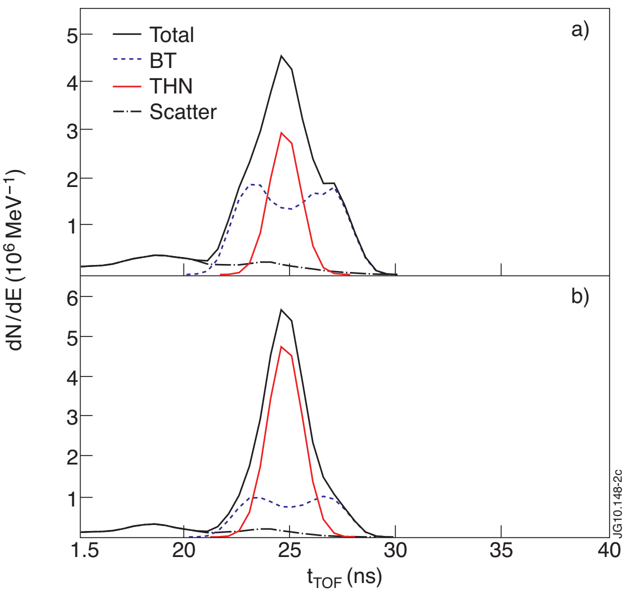

Figure 2: Neutron energy spectra of the fitted components shown in Figure 1.

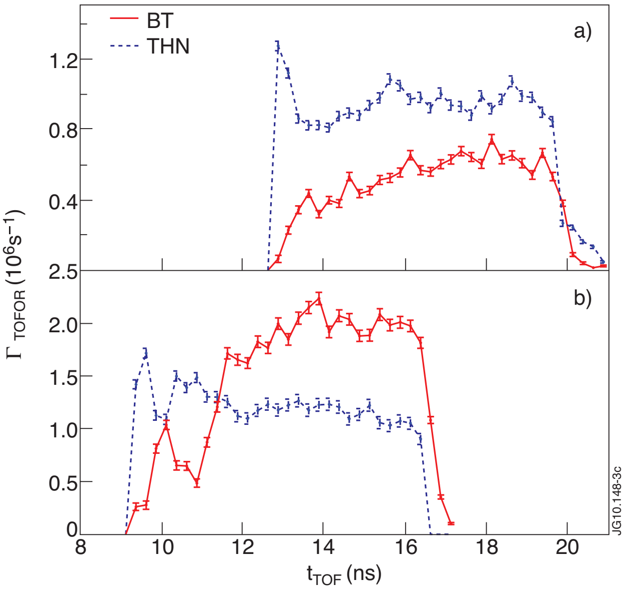

Figure 3: Fitted THN and BT fluxes on TOFOR for Pulse No's: 69992 (a) and 79698 (b).

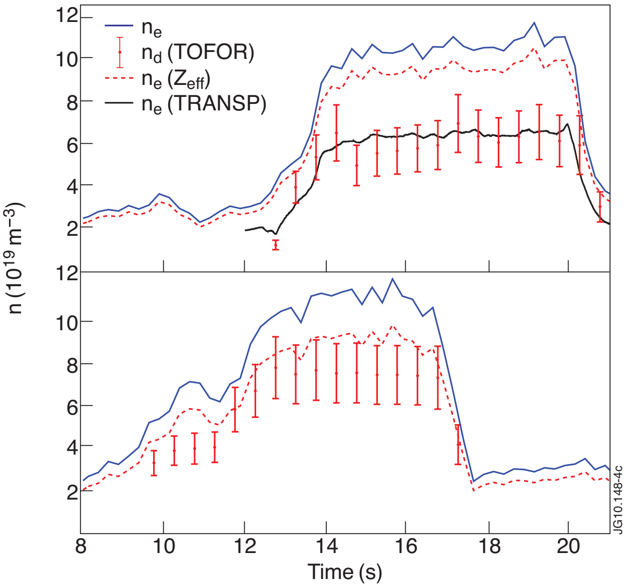

Figure 4: Core electron density (solid blue), core deuterium density deduced from Z_{EFF} (dashed red) and core deuterium density deduced from TOFOR data (points with error-bars) for JET Pulse No's: 69992 (a) and 79698 (b). Optimum core deuterium density for TRANSP is also shown for Pulse No: 69992 (solid black).

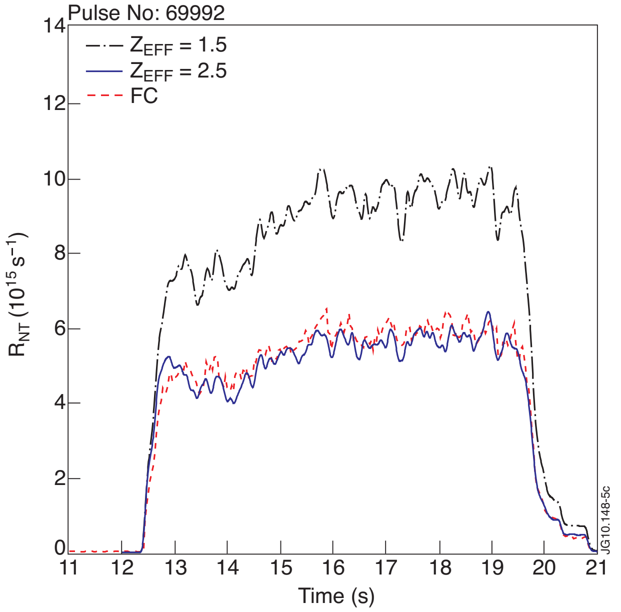

Figure 5: Total neutron rates for JET Pulse No: 69992 measured by fission chambers (dashed red) and predicted by TRANSP (solid blue).

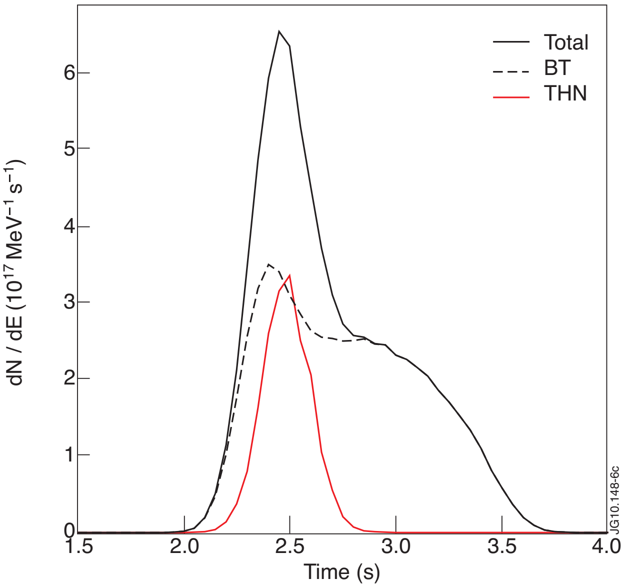

Figure 6: Estimated DD neutron spectrum at ITER showing the THN contribution (solid red) and the BT contribution (dashed blue).